An All-Optical Long-Distance Multi-Gbytes/s Bit-Parallel WDM Single-Fiber Link

L. Bergman, J. Morookian, and C. Yeh, *Fellow, IEEE, Fellow, OSA*

***Abstract*— An all-optical long-distance (>30 km) bit-parallel wavelength division multiplexed (WDM) single-fiber link with 12 bit-parallel channels having 1 Gbyte/s capacity has been designed. That system functionally resembles an optical fiber ribbon cable, except that all the bits pass on one fiber-optic waveguide. This single-fiber bit parallel wavelength link can be used to extend the (speed × distance) product of emerging cluster computer networks, such as, the MyriNet, SCI, Hippi-6400, ShuffleNet, etc. Here, the detailed design of this link using the commercially available Corning DS (dispersion-shifted) fiber is given. To demonstrate the viability of this link, two WDM channels at wavelengths 1530 and 1545 nm carrying 1 ns pulses on each channel were sent through a single 25.2-km long Corning DS fiber. The walkoff was 200 ps, well within the allowable setup and hold time for the standard ECL logic which is 350 ps for a bit period of 1 ns. This result implies that 30 bit-parallel beams spaced 1 nm apart between 1530–1560 nm, each carrying 1 Gbits/s signal, can be sent through a 25.2-km Corning DS fiber carrying information at a 30 Gb/s rate.**

***Index Terms*— Optical fiber communication, optical propagation in nonlinear media, optical pulses, optical solitons, optical waveguides, single-mode fiber, wavelength division multiplexing.**

I. Introduction

Unlike the usual wavelength division multiplexed (WDM) format where input parallel pulses are first converted into a series of single pulses which are then launched on different wavelength beams into a single-mode fiber, the bit-parallel (BP) WDM format was proposed [1], [2]. Under this BP-WDM format, no parallel to serial conversion of the input signal is necessary, parallel pulses are launched simultaneously on different wavelength beams. Time alignment of the pulses for a given signal byte is very important.

There exists a competing non-WDM approach to transmit parallel bits—the fiber optic ribbon approach—where parallel bits are sent through corresponding parallel fibers in a ribbon format. However, it is very difficult to maintain time alignment of the parallel pulses due to practical difficulty in manufacturing identical uniform fibers. Furthermore, it is known that computer vendors would like to apply the same technology to increase the bandwidth of campus network in support cluster computing, and to provide salable external I/O networks for clusters of massively parallel processor (MPP) supercomputers (i.e., multiple network channels connected to one machine). Cluster computing is expected to gain greater importance in the near future as users tap the latent unused computer cycles of company workstations (sometimes in off hours) to work on large problems, rather than buying a specific supercomputer. In DoD applications, it would enable high-performance computers to be deployed in embedded systems. For high-performance computing environments, clusters of MPP supercomputers can also be envisioned. This concept elevates the cluster computing model to a new level. In this case, not only is high bandwidth and low latency required, but now interchannel message synchronization also becomes important among the parallel network channels entering the machine—especially if all machines are tightly coupled together to work on one large problem. In the limit, the aggregate bandwidth required to interconnect two large MPP supercomputers approaches the bisection bandwidth of the internal communication network of the machine. For example, in a 2^n-node hypercube interconnected MPP architecture, there would be up to 2^{n-1} links between each half of the machine (e.g., 1024 processor nodes would have 512 links at 200 Mbytes/s per link, or 102 Gbytes/s total). The need for a single media parallel interconnect is apparent. Thus, the single-fiber WDM format of transmitting parallel bits rather than a fiber ribbon format may be the media of choice.

The purpose of this paper is, first, to present the detailed design of a long distance (32 km) all-optical bit-parallel WDM single-fiber link with 12 bit-parallel channels having 1 Gbyte/s capacity using available components and fiber. The speed-distance product for this link is 32 Gbytes/s-km while the maximum speed-distance product for fiber ribbon is less than 100 Mbytes/s-km.

Then, to demonstrate the viability of this link, two WDM channels at wavelengths 1530 and 1545 nm carrying 1 ns pulses on each channel were sent through a single 25.2-km long Corning DS fiber. The walkoff was 200 ps, well within the allowable setup and hold time for the standard ECL logic which is 350 ps for a bit period of 1 ns.

II. A Review of the Theoretical Foundation

This section provides the theoretical foundation for the wave propagation of parallel pulses on different wavelength beams in a linear/nonlinear fiber.

The fundamental equations governing M numbers of co-propagating waves in a linear/nonlinear fiber including the

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The authors are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA.

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CPM phenomenon are the coupled nonlinear Schrodinger equations [3], [4]

$$\frac{\partial A_j}{\partial z}+\frac{1}{v_{gj}}\frac{\partial A_j}{\partial t}+\frac{1}{2}\alpha_j A_j = \frac{1}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial t^2}-\gamma_j\left(|A_j|^2+2\sum_{m\neq j}^{M}|A_m|^2\right)A_j \quad (j=1,2,3,\cdots M). \tag{1}$$

Here, for the jth wave, $A_j(z,t)$ is the slowly varying amplitude of the wave v_{gj}, the group velocity β_{2j}, the dispersion coefficient $(\beta_{2j}=dv_{gj}^{-1}/d\omega), \alpha_j$, the absorption coefficient, and

$$\gamma_j=\frac{n_2\omega_j}{cA_{\text{eff}}} \tag{2}$$

is the nonlinear index coefficient with A_{eff} as the effective core area and $n_2=3.2\times10^{-16}$ cm^2/W for silica fibers, ω_j is the carrier frequency of the jth wave, c is the speed of light, and z is the direction of propagation along the fiber. (For a linear fiber, the nonlinear coefficient γ_j is zero resulting in the decoupling of copropagating beams, i.e., each beam propagates independently of all other copropagating beams.)

Introducing the normalizing coefficients

$$\begin{aligned}\tau &= \frac{t-(z/v_{g1})}{T_0}\\ d_{1j} &= (v_{g1}-v_{gj})/v_{g1}v_{gj}\\ \xi &= z/L_{D1}\\ L_{D1} &= T_0^2/|\beta_{21}|\end{aligned} \tag{3}$$

and setting

$$u_j(\tau,\xi)=(A_j(z,t)/\sqrt{P_{0j}})\exp(\alpha_j L_{D1}\xi/2) \tag{4}$$

$$\begin{aligned}L_{NLj} &= 1/(\gamma_j P_{0j})\\ L_{Dj} &= T_0^2/|\beta_{2j}|\end{aligned} \tag{5}$$

gives

$$\begin{aligned}i\frac{\partial u_j}{\partial \xi} &= \frac{\text{sgn}(\beta_{2j})L_{D1}}{2L_{Dj}}\frac{\partial^2 u_j}{\partial \tau^2}-i\frac{d_{1j}}{T_0}L_{D1}\frac{\partial u_j}{\partial \tau}\\ &\quad -\frac{L_{D1}}{L_{NLj}}\left[\exp(-\alpha_j L_{D1}\xi)|u_j|^2 + 2\sum_{m\neq j}^{M}\exp(-\alpha_m L_{D1}\xi)|u_m|^2\right]u_j\\ &\quad (j=1,2,3,\cdots,M).\end{aligned} \tag{6}$$

Here, T_0 is the pulse width, P_{0j} is the incident optical power of the jth beam, and d_{1j}, the walk-off parameter between beam 1 and beam j, describes how fast a given pulse in beam j passes through the pulse in beam 1. In other words, the walk-off length is

$$L_{W(1j)}=T_0/|d_{1j}|. \tag{7}$$

So, $L_{W(1j)}$ is the distance for which the faster moving pulse (say, in beam j) completely walked through the slower moving pulse in beam 1. The nonlinear interaction between these two optical pulses ceases to occur after a distance $L_{W(1j)}$. For cross-phase modulation (CPM) to take effect significantly, the group-velocity mismatch must be held to near zero.

It is also noted from (6) that the summation term in the bracket representing the cross-phase modulation (CPM) effect is twice as effective as the self phase modulation (SPM) effect for the same intensity. This means that the nonlinear effect of the fiber medium on a beam may be enhanced by the copropagation of another beam with the same group velocity.

Equation (6) is a set of simultaneous coupled nonlinear Schrodinger equations which may be solved numerically by the split-step Fourier method, which was used successfully earlier to solve the problem of beam propagation in complex fiber structures, such as, the fiber couplers [5], and to solve the thermal blooming problem for high-energy laser beams [6]. According to this method, the solutions may be advanced first using only the nonlinear part of the equations. And then the solutions are allowed to advance using only the linear part of (6). This forward stepping process is repeated over and over again until the desired destination is reached. The Fourier transform is accomplished numerically via the well-known fast Fourier transform Technique.

This nonlinear interaction of copropagating beams, for short, high-intensity pulses, is the subject of intense research. Some of the preliminary results have been published [4].

III. Elements of a 12-Bit Parallel WDM System

Let us now return to the design of our BP-WDM system. Due to the relatively broad pulsewidths (~1 ns) and low power levels of the data pulses, nonlinear interaction of copropagating pulses can be consider to be negligible [8]. It is expected that 12 separate beams will be used. Anticipating the use of erbium amplifier, beam separation among these 12 beams must be limited by the useful bandwidth of the erbium amplifier which is from 1535 to 1560 nm. Hence, separation between neighboring beams must be less than 25/12 = 2.08 or 2 nm. A block diagram of the link is shown in Fig. 1.

A. The Transmitter

The transmitter of the system consists of 12 discreet distributed-feedback laser diodes [9] and a 16-to-1 fiber coupler. Each laser element is selected to fall within the erbium gain bandwidth at a preselected $\Delta\lambda$ from its neighbors. To minimize system cost, the lasers are directly modulated with NRZ data at a rate up to 1 Gb/s each, for an aggregate of 1 Gbyte/s. The timing of the bits in any word are aligned at the input to the fiber link by adjusting the phase of the laser drive signal for each bit using conventional electrical delay components. The optical power coupled into the fiber arms at the input to the 16-to-1 coupler is about 0 dBm (i.e., 1 mW).

B. The Single-Mode Fiber

Corning DS fiber is chosen to be the single-mode fiber for this system because of its desirable dispersion characteristics [7]. The dispersion characteristics of this fiber is shown in Fig. 2. It is seen that for the wavelength range of interest (1535–1560 nm), the dispersion coefficient, $|\beta_2|$, is around 2

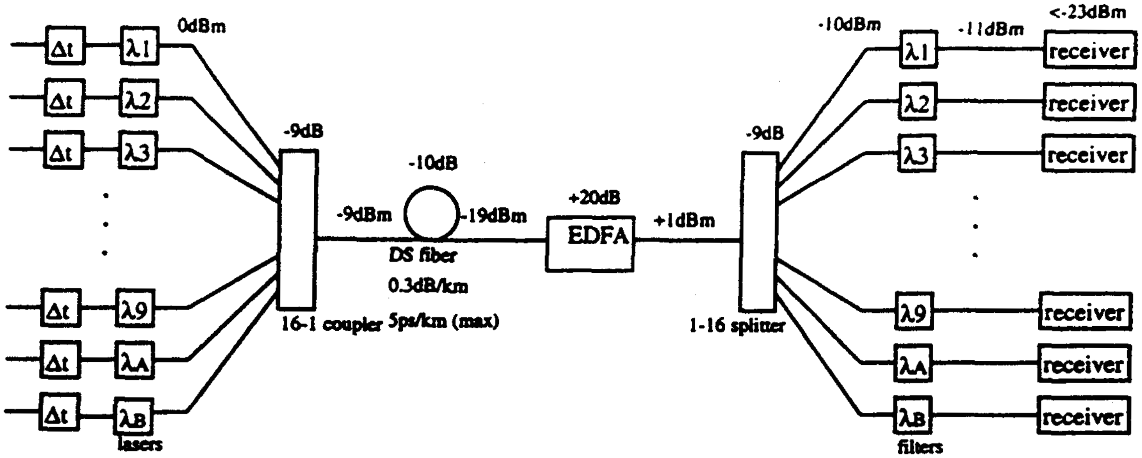

Fig. 1. Block diagram for an all-optical 12 channel bit-parallel WDM single-fiber system.

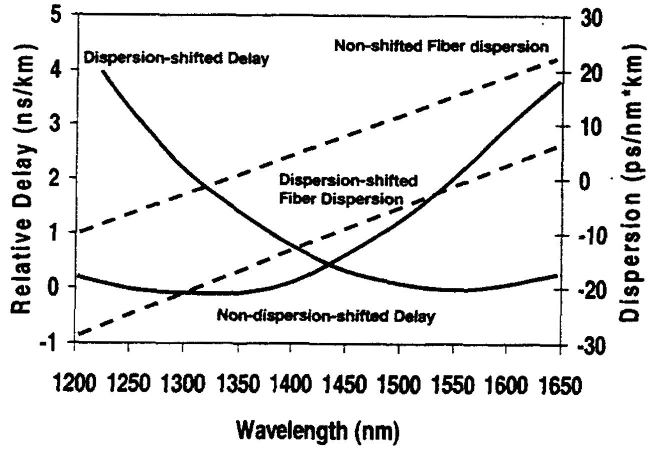

Fig. 2. Dispersion characteristics of Corning DS fiber.

ps^2/km. The difference of group velocities as a function of the wavelength of the beams have been measured and are displayed in Fig. 3. It is seen that the maximum difference in group velocity over the wavelength of interest is 5 ps/km. An erbium-doped fiber amplifier (EDFA) is used to boost the power at the receiver.

C. The Receiver

The receiver of the system consists of a 1-to-16 fiber splitter, 12 optical bandpass filters, and 12 fiber-optic receivers.

IV. Design Considerations

A. Wavelength Spacing Consideration

A 1 Gbyte/s, each bit path must have a minimum bandwidth of 2 GHz to reproduce the data. In estimating the spread of the optical spectrum of each laser element, a 4 GHz bandwidth will be assumed. The spread of each element's spectrum $\Delta\lambda$ is then 0.032 nm for a 4 GHz bandwidth which is well within the 2 nm beam separation between neighboring beams. It should be noted that any spectral broadening of the pulse due to chirp or other factors will be much less than the 2 nm beam separation that has been used for our system. Furthermore, the 2 nm beam separation also lessens the demand on the optical bandpass filters used to separate the WDM beams at the receiver end.

B. Skew and Walk-Off Consideration

At 1 Gb/s, the bit period is approximately 1 ns. For the worst case, the setup and hold time for standard ECL logic is 350 ps. This means that there is a leeway of (1000-350)/2 = 325 ps in which the pulses may drift away from each other. If one limits the skew or walkoff to half of 325 ps, then the maximum length of fiber which can be used is 160/5 = 32 km.

C. Loss Consideration

For a maximum length of 32 km, it is clear that an EDFA will be needed to increase the power at the receiver. As indicated in Fig. 1, a gain of 20 dB via the EDFA will provide a gain margin of more than 12 dB at the receiver.

V. Experimental Demonstration of a Two Wavelengths BP-WDM System

The experimental setup is shown in Fig. 4. Two beams from two laser diodes whose wavelengths are 1530 and 1545 nm, are modulated by nano-second size pulses. These beams whose spectral shapes are displayed in Fig. 5, are coupled simultaneously into a Corning DS fiber. A picture of the pulses on these two beams before they were launched into the fiber is shown in Fig. 6. It is seen that these nano second size pulses were well aligned at the entrance of the fiber link.

The spool of Corning DS fiber used for our experimental link was 25.2 km long. The output was displayed in Fig. 7. One can readily measure the shift or the walkoff between these pulses—it was 200 ps or 6 ps/km. This result is consistent with our previous measurement displayed in Fig. 3. There, the walkoff was measured between a tunable ring laser and a 1545-nm laser diode.

It is noted that the experimentally measured walkoff of 200 ps for this two wavelength BP-WDM demonstration is well within the allowable setup and hold time for the standard ECL logic which is 350 ps for a bit period of 1 ns.

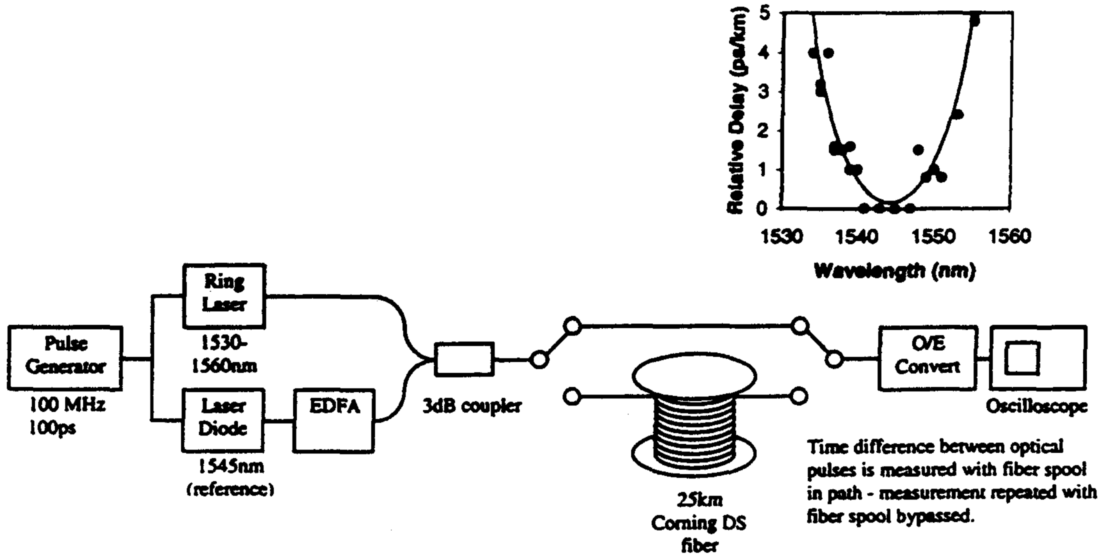

Fig. 3. Measured group velocity differences for different wavelength beams. The sources are a tunable ring laser and a DFB laser diode at 1545 nm.

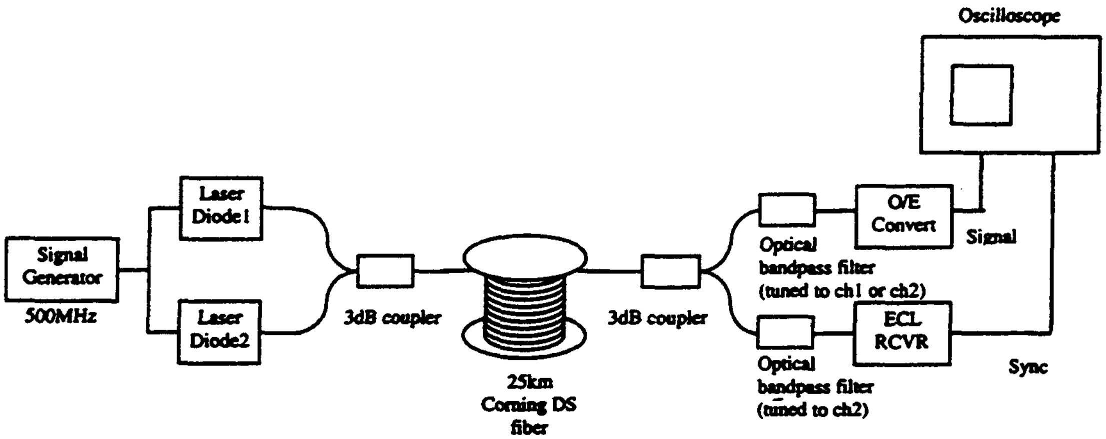

Fig. 4. The experimental setup for the measurement of bit-parallel nanosecond pulses propagating on two beams at 1530 and at 1545 nm in a 25.2-km long Corning DS fiber.

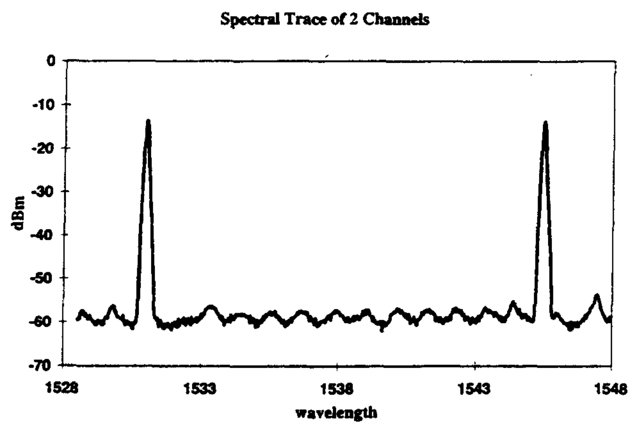

Fig. 5. Spectral shapes for the two copropagating beams.

VI. Conclusion

This paper shows that, using available components and fiber, one can design a 32-km BP-WDM single-fiber data link with 1 Gbyte/s capacity. This is an all-optical link with byte-wide optical path which can bypass any electrical bottleneck. A demonstration link can be readily built between JPL and Caltech for HIPPI 6400 using this design.

It was also shown through an actual experiment that nanosecond size pulses on two BP-WDM beams at 1530 and 1545 nm can be successfully transmitted through a 25.2-km long Corning DS fiber with acceptable walkoff which is well within the allowable setup and hold time of standard ECL logic circuits. As can be seen from Fig. 3 that the maximum walkoff between any beams located within the wavelength range of 1530 and 1560 nm is 200 ps. This result implies that 30 bit-parallel beams spaced 1 nm apart from 1530 to 1560 nm, each carrying 1 Gb/s signal, can be sent through a 25.2-km Corning DS fiber at an information rate of 30 Gb/s. This means that the speed-distance product for this link is about 94 Gbytes/s-km, a number way beyond the best that fiber ribbon can offer.

An all-optical adaptive bit alignment scheme for future ultrahigh-capacity BP-WDM link with 10-ps bit pulses is being studied using our newly developed shepherding pulse technique [4].

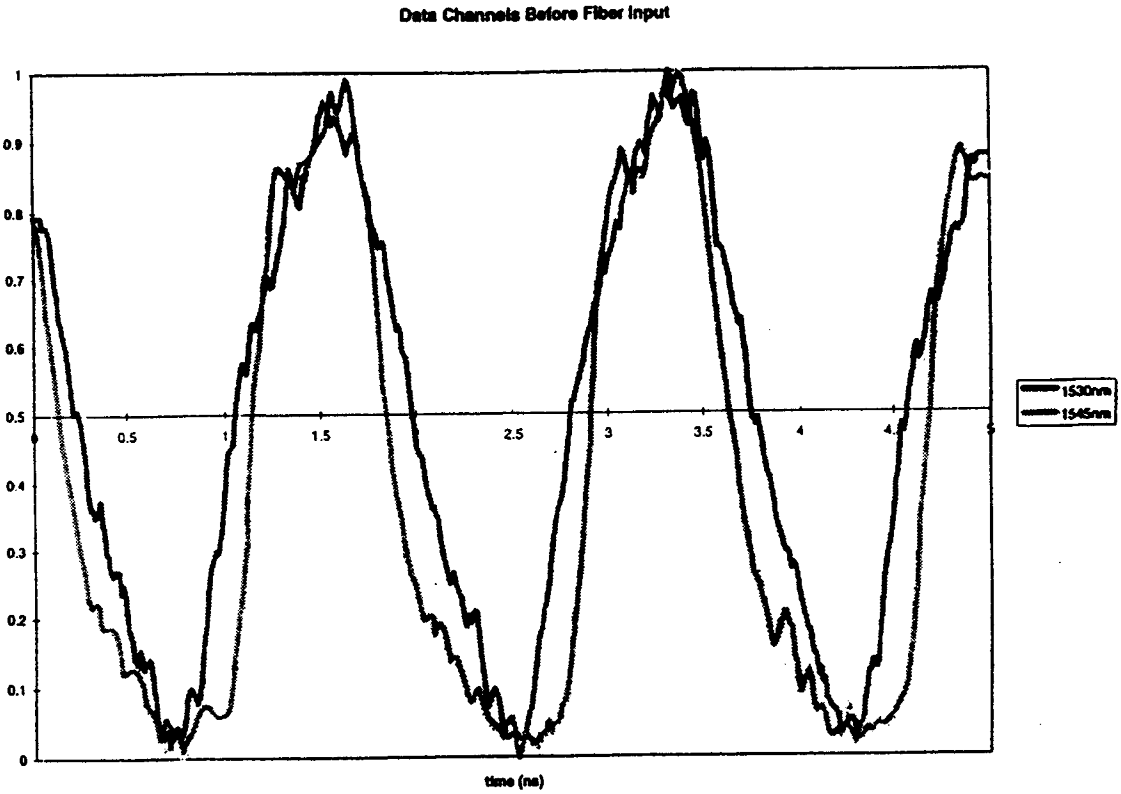

Fig. 6. A picture of the nanosecond pulses on the two copropagating beams before entering the fiber. These pulses are very well aligned at the entrance to the fiber link.

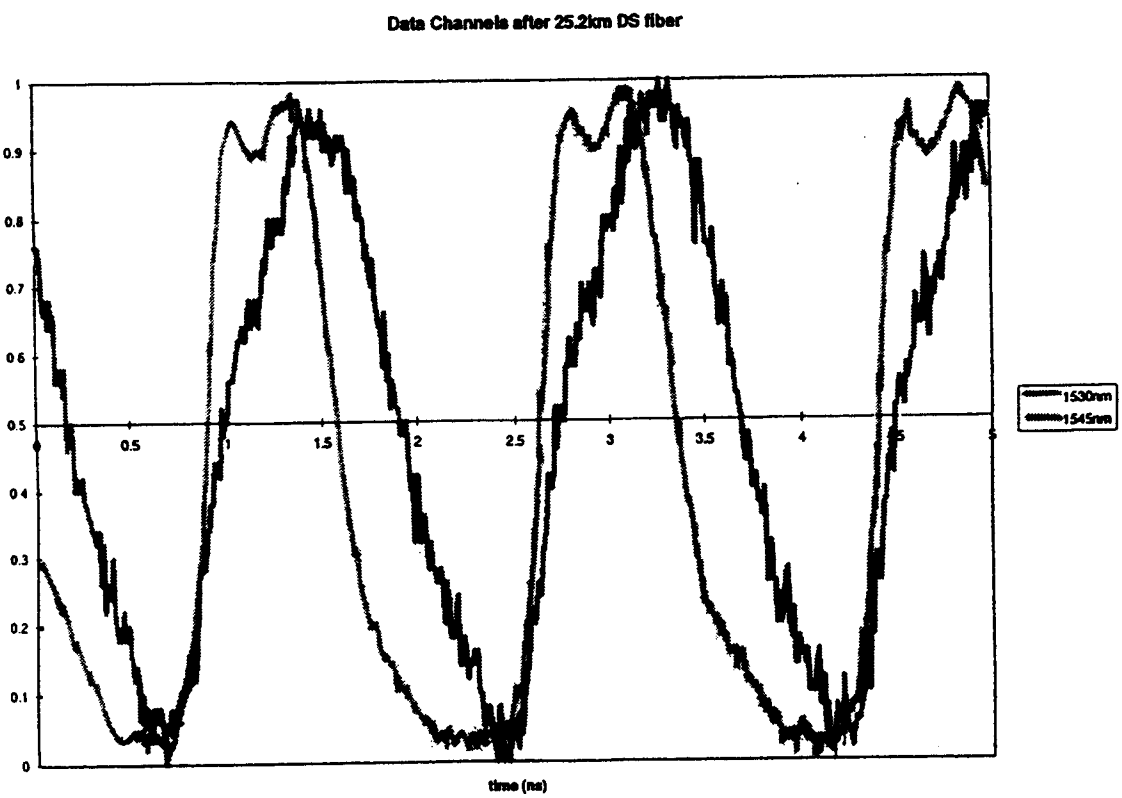

Fig. 7. A picture of the nanosecond pulses on the two copropagating beams after passing through 25.2 km of the fiber. The alignment of the two pulses is shifted 200 ps at the output of the fiber link. This shift represents the walkoff among these different wavelength beams.

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L. Bergman received the M.S. degree from the California Institute of Technology (Caltech), Pasadena, and the Ph.D. degree from Chalmers University of Technology, Gothenburg, Sweden, both in electrical engineering.

For the past 25 years, he has worked at the Jet Propulsion Laboratory (JPL), Pasadena, CA, in the area of fiber-optic local area networks, terabit all-optical computer networks, fiber-optic sensors, and optical interconnections for computers. He has authored over 80 papers in the fields of fiber optics and high-speed communications, received four patents, and lectured at local universities. In 1984, he was awarded the first place prize at the European Conference on Optical Communication (ECOC), Stuttgart, Germany, for a new system approach that achieves 5 Gbits/s data rates for ring LAN's. In 1993, he earned the Technology and Applications Program (TAP) Directorate Exceptional Service Award for sustained research contributions to the fields of fiber-optic network and supercomputer optics, motion picture, and data processing industries as well as nearby universities in the areas of electrooptic system design, telecommunications, and computer science. He presently is the Deputy Manager of the Information and Computing Technologies Research Section, and is also the Project Engineer for the JPL Supercomputer Center.

Dr. Bergman is a member of Tau Beta Pi, Eta Kappa Nu, Phi Kappa Phi, and Sigma Xi.

J. Morookian received the B.S. degree in electrical engineering in 1991 from the University of Southern California (USC), Los Angeles.

He subsequently assumed a full-time position at the Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, in May 1991. During his four graduate years as a National Merit Scholar at USC, he worked at the Center for Laser Studies, furthering research in optical memory systems, power-by-light applications, and optical code division multiple access (CDMA). As a member of the High-Speed Optical Systems Group at JPL, he has worked on several optical networking projects, including an optical CDMA scheme; fempto-second laser pulse source; high-speed time division multiplexing (TDM), and high-speed wavelength division multiplexing (WDM). He has coauthored several papers on these subjects.

Mr. Morookian is a member of the USC Engineering Honors Group, Alpha Lambda Delta, and Tau Beta Pi.

C. Yeh (S'56–M'63–SM'82–F'85) received the B.S., M.S. and Ph.D. degrees in electrical engineering from the California Institute of Technology (Caltech), Pasadena, in 1957, 1958, and 1962, respectively.

In 1962, he joined the University of Southern California, Los Angeles, as an Assistant Professor of Electrical Engineering and became an Associate Professor in 1967. He moved to the University of California at Los Angeles (UCLA) in 1967 as an Associate Professor of Electrical Engineering and became a Professor in 1972. Throughout more than 30 years of his professional career, he was a consultant to many industrial companies, such as the Hughes Research Laboratories, The Dikewood Corporation, the Aerospace Corporation, etc. Starting in 1992, he left UCLA and has been a Consulting Engineer at the Jet Propulsion Laboratory, Pasadena, CA. He has published more than 120 papers in fiber optics and applied electromagnetic waves, where many of his publications are widely cited. Examples of his key research are propagation of wavelength division multiplexed soliton pulses in a nonlinear fiber, ceramic ribbon waveguide—an ultralow-loss (less than 5 dB/km) millimeter/submillimeter dielectric waveguide, a random-access protocol for unidirectional ultrahigh-speed (multigigabit rate) optical fiber network, single-mode optical waveguides by the vector finite-element method, propagation of optical waves in an arbitrarily shaped fiber, fiber couplers, or integrated optical circuit by the scalar beam propagation method, scattering of a single submicron particle by focused laser beams, scattering of electromagentic waves by arbitrarily shaped dielectric bodies, reflection and transmission of electromagnetic waves by a relativistically moving dielectric slab or halfspace, diffraction of waves by an elliptical or parabolic dielectric cylinder, and elliptical dielectric waveguides or optical fibers, etc.

Dr. Yeh is a member of Eta Kappa Nu and Sigma XI and a Fellow of the Optical Society of America (OSA).